MICROMACHINED STACK COMPONENT FOR MINIATURE THERMOACOUSTIC REFRIGERATOR

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ABSTRACT

This paper reports a novel miniature MEMS based thermoacoustic refrigerator design for thermal management of electronic and optoelectronic devices. This technique utilizes high-frequency acoustic energy to provide the heat pumping effect. The goal of the Rockwell Scientific-led HERETIC (Heat Removal by Thermo-Integrated Circuits) project is the development and demonstration of a miniaturized refrigeration device based on the thermoacoustic refrigeration principle.

Utilizing MEMS technology such as high aspect ratio through wafer etching, bonding and coating techniques, three to four mm thick bonded MEM-TAR (Thermoacoustic Refrigerator) stacks with only 10 to 15 micron wide fine patterns were demonstrated.

With our current design, numerical models predict device capability of 1 W heat transport at 20 °C below ambient when pressurized with 10 atm of He/Ar gas mixture. Preliminary results using 1 atm air achieve as high as 10 degrees of stable cooling below ambient.

INTRODUTION

A thermoacoustic refrigerator consists of a resonance tube that houses a stack of parallel plates, heat exchangers and an acoustic driver. By exciting a standing wave within the resonance tube, a temperature difference develops across the stack, thereby enabling heat exchange between two heat exchangers. This phenomenon has attracted interest as a possible means for cooling using environmentally benign gases such as mixture of He and Argon.

The development of a chip-size MEM-TAR device is an attractive refrigerative thermal management technology for cooling of moderate power electronic components. It benefits from being compact, solid state, actively controllable, and retrofit compatible. Advantages of the technique over alternate management solutions include:

- Increase reliability because of no mechanical moving parts.
- Higher efficiency and lower operating current than semiconductor-based refrigeration technologies (such as thermoelectronic and thermoionic devices).
- True refrigeration operation, in contrast to dissipative techniques (convective and conductive), allowing operation under high ambient temperature conditions.

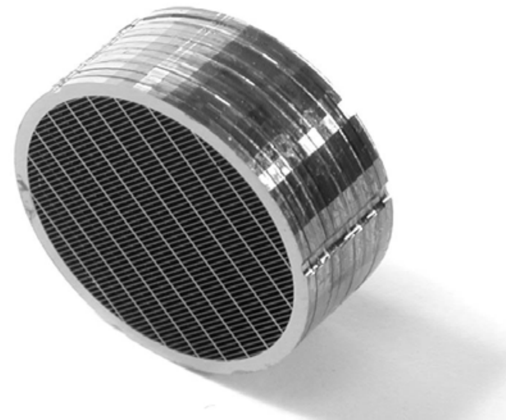

Figure 1. A bonded MEM-TAR core device coated with 15 micron thick parylene.

- No liquid coolants (as for spray cooling technologies) or ozone-depleting chemicals.

To maximize heat pumping of the MEM-TAR, the micromachined core component must provide a large surface area with specific gap dimensions and low blockage ratio. With each device configuration and operating pressure, a specific stack spacing approaching the mean free path can improve efficiency. Using MEMS technology, this paper demonstrates a novel process design to fabricate high aspect ratio MEM-TAR core stack structures. With the ability of performing through wafer deep silicon etching without undercut, we have demonstrated bonded MEM-TAR core devices as thick as 4.2 mm thick with estimated 170cm^2 per cubic centimeter surface area, greater than 90% of air to solid ratio and extremely high aspect ratio of etch patterns. Furthermore, the stacked device has been conformably coated with parylene to increase the thermo-resistivity of the silicon base core structure.

TAR CORE COMPONENT DESIGN AND FABRICATION

The MEM-TAR system design has been theoretically analyzed based on a low amplitude linear acoustics model using DeltaE program and CFD modeling tools. The design requirements (cooling load, temperature difference, drive ratio), material related issues (working gases, stack

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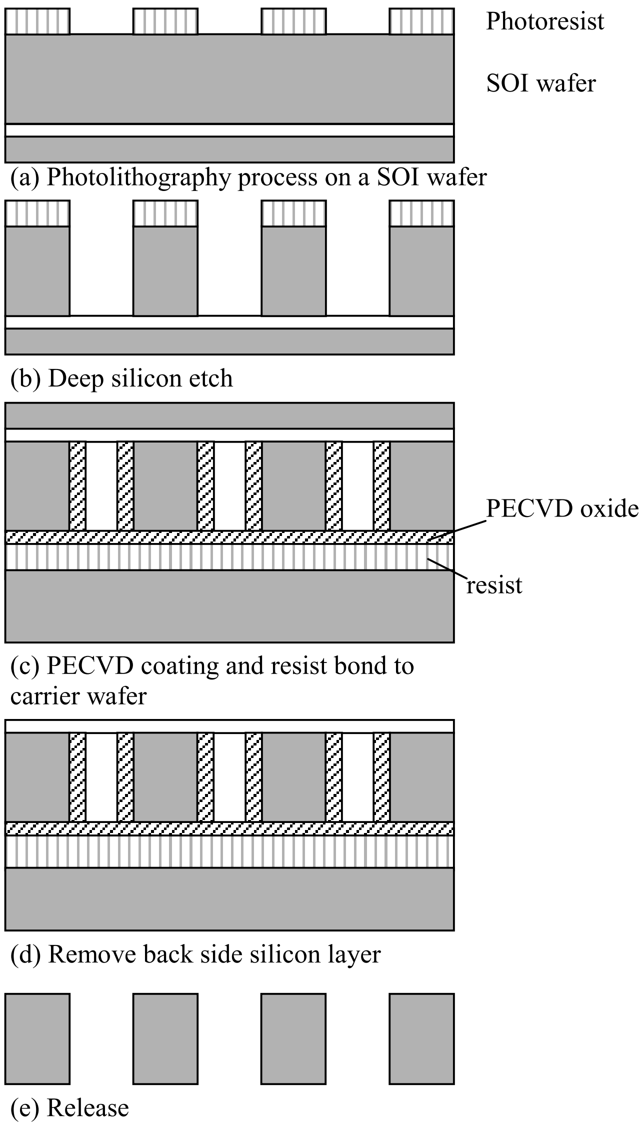

Figure 2. Schematic of MEM-TAR stack fabrication process

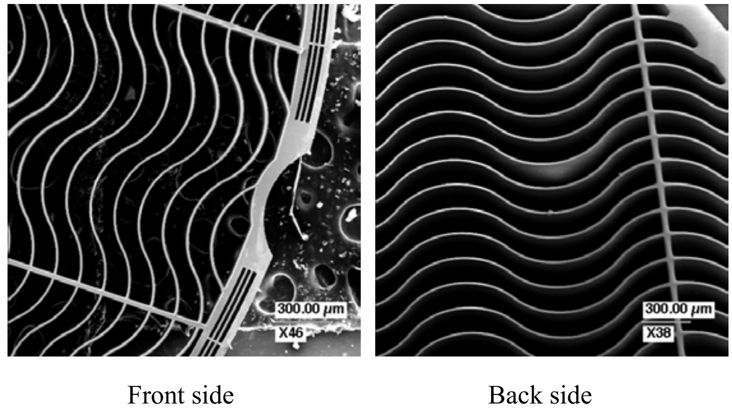

Figure 3. SEM micrographs of the front and backside of a released stack showing no undercut at the buried oxide surface (right).

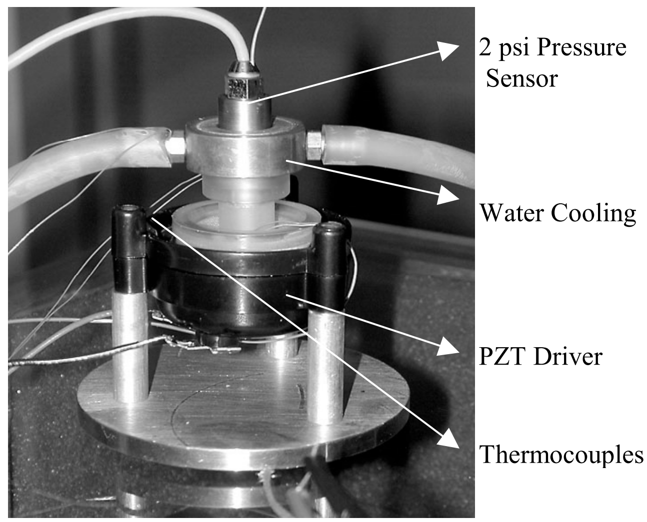

Figure 4. Overview of a miniature thermoacoustic refrigerator integrating the micromachined stack structure

material), and geometry related parameters (stack length, location, spacing, resonance tube sizes, stack size, location and material blockage ratio) were examined.

TAR core components with specific spacing and stack length were fabricated according to specific thermo-acoustic refrigerator designs. Figure 1 shows an example of a 4.2 mm thick stacked core component with 127-micron spacing between parallel plate structures. The diameter of the bonded stack is 10.5 mm.

A cross-section of the fabrication process is shown schematically in Figure 2. The process starts with an SOI wafer with substrate thickness range from 400 to 500 microns. Lithographic process is first used to put a 11 to 12 micron thick patterned resist mask on the substrate, and an ICP STS etcher was used to etch through the wafer, stopping on the oxide layer. The remaining resist layer is stripped with an O2 plasma and the etched wafer is coated with PECVD oxide as a protection layer. The wafer is turned over and bonded to a carrier wafer with photoresist and the remaining silicon layer is further selectively removed via plasma etch. Finally, devices are separated from the carrying wafer, cleaned, BHF dipped and collected. The released dies are aligned, bonded and coated with 10 to 15 micron thick parylene. Figure 3 shows SEM micrographs of a released stack with no undercut on the back side and perfect pattern transfer via the anisotropic deep silicon etch recipe we developed. An aspect ratio as high as 50 to 1 with a 10 micron wide rib size was achieved.

EXPERIMENTAL WORK AND RESULTS

Figure 4 shows close-up details of a ¼ wavelength miniature thermoacoustic refrigerator. The hot side heat exchanger is equipped with a built-in water cooling channel for stable operation. The length of the whole device is about 2 inches, with resonance frequency at around 4 kHz. An integrated data acquisition system is built and shown in Figure 5. This system allows fast iteration and accurate testing on various MEM-TAR core designs. All measurement data, including operating current, voltage, and power into the PZT driver, phase, resonance frequency, acoustic pressure and temperature reading on both cold and hot side heat exchangers, can be recorded in real time for analysis.

With our current miniature size and ¼ wavelength design, the numerical model predicts a cooling capability of 1 W at 20 degrees C below ambient when pressurized with 10 atm of He/Ar gas mixture. Preliminary results using just 1 atm air have achieved as high as 10 degrees of stable cooling. A pressurized version is being developed. Figure 6 shows a typical result of the cold side of a MEM-TAR stack operating under 1 atm air.

CONCLUSION

A miniature thermoacoustic refrigerator with novel micromachined stack component was designed and fabricated. Using MEMS process technology, a bonded MEM-TAR core device with estimated 170cm^2 per cubic centimeter surface area, greater than 90% of air to solid ratio and extremely high aspect ratio of etch patterns were achieved.

Preliminary result using just 1 atm air achieves 10 degrees of stable cooling. A high-pressurized version being developed is expected to improve device performance even further.

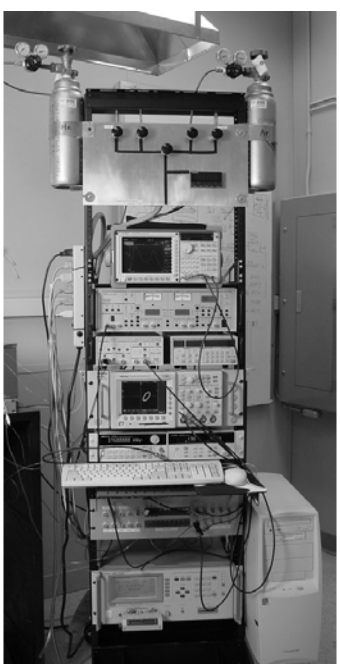

Figure 5 Thermoacoustic test bed

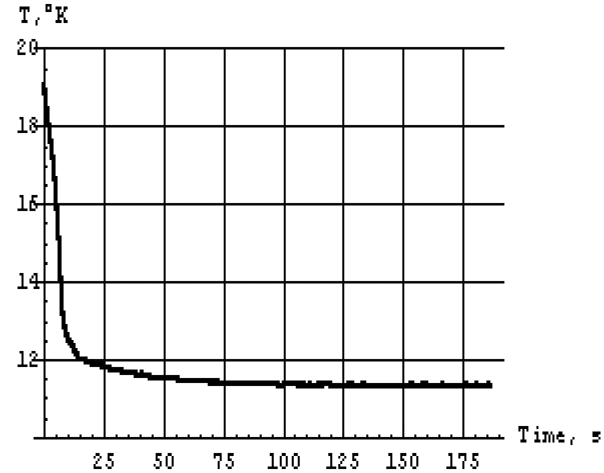

Figure 6 Temperature at the cold exchanger

ACKNOWLEDGMENTS

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